MITIGATION OF CONFINED EXPLOSION EFFECTS BY PLACING WATER IN PROXIMITY OF EXPLOSIVES

By

W.A. Keenan and P.C. Wager
Structures Division, Code L51
Naval Civil Engineering Laboratory
Port Hueneme, CA 93043-4328

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ABSTRACT

Water, placed in the near proximity of a confined explosion, can mitigate the gas pressure loading developed inside a structure confining an explosion. This phenomenon can be exploited in the design and operation of new and existing facilities exposed to a potential internal explosion. This water concept offers the potential for major savings in the cost for explosives safety of ordnance facilities from accidental explosions, for survivability of combat facilities from enemy weapons, and for physical security of sensitive facilities from terrorist bombings.

This paper describes the mechanism by which water absorbs energy from a confined explosion and how this phenomenon reduces the gas pressure loading from a confined explosion; presents test data demonstrating that water can indeed mitigate the gas pressure loading from a confined explosion; describes how water could be exploited in the design of facilities impacted by confined explosions, and estimates the benefits derived from water, in terms of the reduction in land area encumbered by hazardous debris from unhardened ordnance facilities, reduction in the cost of structures designed to fully or partially contain the effects from an internal explosion, and the increase in the safe explosive limit for existing ordnance facilities.

1.0 INTRODUCTION

1.1 Purpose

This paper describes how water, placed in the near proximity of a confined explosion, can mitigate the gas pressure loading developed inside the structure confining the explosion, and how this phenomenon can be exploited in the design and operation of new and existing

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facilities exposed to a potential internal explosion. This water concept offers the potential for major savings in the cost for explosives safety of ordnance facilities from accidental explosions, for survivability of combat facilities from enemy weapons, and for physical security of sensitive facilities from terrorist bombings.

1.2 Background

In early 1991, the Carderock Division, Naval Surface Warfare Center (NSWC), Code 1740.2, conducted high explosive tests for the Naval Civil Engineering Laboratory (NCEL). These tests support NCEL development of the High Performance (HP) Magazine.

The HP Magazine is a multi-cell, earth-covered, R/concrete, box-shaped structure with a tunnel entrance. Ordnance is stored in the cells. The cells are designed to prevent an inadvertent detonation in any storage cell from causing sympathetic detonation of ordnance stored in any other cell. Consequently, the maximum credible explosion (MCE) for the HP Magazine is the net explosive weight (NEW) capacity of a single cell.

The NSWC tests were designed to measure the benefit of constructing HP cells using water-filled walls in order to reduce the peak gas pressure and total gas impulse generated by the MCE in the confined space of an HP Magazine. The test results demonstrated that water, placed in the near proximity of a potential explosion, can reduce the peak gas pressure and total gas impulse from a confined explosion by as much as 90 percent, at least for the range of test parameters investigated!

In late 1991, the Naval Weapons Station, Concord, California, contracted NCEL to determine the safe explosive limit for the Radiography Building 35, Pittsburg, California. The normal explosive limit for Building 35 was 5,000 lb NEW but the AMHAZ Review Board reduced the limit to 50 lb NEW until a study could show a higher limit is safe. Building 35 faced shut-down due to inefficient operations unless the limit could be increased to at least 1,680 lb NEW. The NCEL study concluded that the safe explosive limit for Building 35 is less than 10 pounds NEW for protection of people and property at the nearby government property line from hazardous roof debris caused by an inadvertent explosion inside the building (Ref 1). However, NCEL proposed a risk mitigation strategy that increases the safe explosive limit to at least 2,240 pounds NEW by replacing the roof system and requiring a water blanket to be draped over each pallet of ordnance when the pallet is anywhere inside Building 35 (Ref 2). The cost-benefit of this risk mitigation strategy is very high and expected to prevent shut-down of Building 35.

The dramatic benefits derived to date suggest that water, deployed in very specific ways, may prove to be one of the best strategies for mitigating the effects from confined explosions since the discovery of high explosives! Hence, publication of this paper which attempts to capture the potential applications and benefits of water in the design and operation of new and existing facilities exposed to a potential internal explosion.

1.3 Scope

This paper provides the following information:

- Describes the mechanism by which water absorbs energy from a confined explosion.

- Presents test data demonstrating that water can indeed mitigate the effects from a confined explosion, at least within the range of current test data.

- Identifies the types of Naval facilities that are designed to control confined explosions and describes how the benefits of water could be exploited.

- Presents a gross description of concepts for deploying water in various types of facilities to optimize its effectiveness in mitigating effects from confined explosions.

- Estimates the benefits derived from water, in terms of the reduction in land area encumbered by hazardous debris from unhardened ordnance facilities, the reduction in the cost of structures designed to fully or partially contain the effects from an internal explosion, the increase in the safe explosive limit for existing ordnance facilities and bomb disposal devices, and the increased survivability of Command and Control Centers against enemy weapons.

- Identifies the design criteria and research and development needed to exploit the benefits of water in mitigating effects from confined explosions.

2.0 PROBLEM

2.1 Confined Explosion

An explosion in a confined space causes the accumulation of high-temperature gases from the by-products of the explosion. These high-temperature gases, if expanding in a space with restricted venting, cause the buildup of gas pressures inside the structure. The magnitude of the peak gas pressure depends primarily on the weight of explosive relative to the volume of the structure. The duration and total impulse of the gas pressure depend primarily on the degree of venting available for these gases to escape from the structure. The degree of venting, in turn, depends on the area of openings and volume of space in the building envelope, the mass and strength of the building envelope, and the magnitude and location of the explosion inside the structure. The degree of confinement and venting in most facilities is sufficient to produce significant gas pressure loads inside the structure.

2.2 Debris Hazard

Most Navy ordnance facilities used for the production, maintenance, assembly and repair of weapons are conventional (unhardened), above-ground buildings containing less than 30,000 lbs NEW. These ordnance buildings must be sited a large distance from nearby inhabited facilities in order to limit the risk of injuries and damage from hazardous debris produced by the maximum credible explosion (MCE) in the ordnance facility.

The minimum safe separation distance from an ordnance facility encumbers a large area of land. For example, the safe separation distance to inhabited facilities is 1,250 feet minimum for an MCE $\leq$ 30,000 pounds NEW. Thus, an ordnance facility containing less than 30,000 pounds NEW, a common situation, encumbers at least 112 acres of land (the area of a circle with a 1,250 feet radius). The safe separation distance and encumbered land area are dictated by the strike range of hazardous fragments and debris. At today's real estate prices, expecially near the Navy waterfront, the value of encumbered land often exceeds the acquisition cost of the ordnance facility!

The safe separation distance from building debris is dictated, in part, by the gas impulse developed when the explosion is confined by the building envelope. This gas impulse contributes significantly to the launch velocity of building debris and the resulting maximum strike range of hazardous debris. Thus, any scheme that reduces the magnitude of this gas impulse would significantly reduce the maximum strike range of hazardous debris and the corresponding encumbered land area needed for the safety of people and property.

2.3 Containment Structures

Containment structures are hardened structures designed to control the escape of blast pressures, weapon fragments, and facility debris from the MCE inside the structure. Containment structures are designed to either fully or partially contain effects from the MCE.

The TRIDENT Reentry Body Complex, Kings Bay, Georgia, is an example of a full containment structure (Ref 3). Several rooms in this facility were designed to fully contain MCE effects within the room in order to satisfy explosives and contamination safety objectives. The MCE for several relatively large rooms was only 30 lb NEW. The rooms ranged in size from 26,411 ft^3 for explosive storage rooms to 98,172 ft^3 for warhead maintenance rooms. Thus, the high-temperature gases were generated by a relatively small MCE and were allowed to expand in a relatively large space, i.e., the maximum explosive weight (W) to room volume (V) was quite small ($3 \times 10^{-4} \leq W/V \leq 11 \times 10^{-4}$ lb/ft^3). Yet, the gas pressure loading, not just the shock pressure loading, dictated the design of the R/concrete walls, ceiling, and doors needed to fully contain effects from the MCE. Any scheme that would have reduced the magnitude of the gas impulse from the MCE would have significantly reduced the structural cost to fully contain MCE effects within the room. Alternatively, any scheme that would reduce the magnitude of the

gas impulse could be deployed today in the existing Reentry Body Complex, thereby increasing the safe explosive limit for the rooms!

The NAVFAC standard design for a missile test cell (MTC) is an example of a partial containment structure (Ref 4). The MTC is used to test all-up-round missiles which could detonate accidently during the test. The test is conducted remotely from an adjoining Missile Maintenance Facility. The MTC partially contains effects from the MCE, and vents effects in a safe direction away from the adjoining Missile Maintenance Facility. The MTC design is a massive R/concrete, box-shaped structure. Three walls, the floor, the roof, and the access door are hardened designs that prevent the escape of blast pressures, weapon fragments, and facility debris. The fourth wall is a frangible surface designed to fail and blow away under the force from the MCE, thereby venting MCE effects in a safe direction away from the adjoining Missile Maintenance Facility. The frangible wall area and mass, structure volume, and MCE magnitude are in a range that constitutes a partially confined explosion, in which significant gas impulse develops inside the MTC. This gas impulse, in combination with the shock impulse, dictates the structural design of surfaces that are hardened to prevent these surfaces from venting effects from the MCE. Thus, any scheme that would reduce the magnitude of the gas impulse from the MCE would significantly reduce the structural cost to harden the MTC. Alternatively, any scheme that would reduce the magnitude of the gas impulse could be deployed today in many existing MTCs, thereby increasing significantly their safe explosive limit!

2.4 Combat Survivability

Special combat facilities, such as Navy Command and Control Centers, are designed to protect operations from enemy weapons. This performance objective is very difficult to achieve, given the extreme accuracy and penetrating power of today's weapons. Even massive amounts of reinforced concrete, steel, soil cover, and rock rubble can fail to prevent today's weapons from perforating an interior space. Once inside the structure, detonation of the warhead constitutes a fully confined explosion, developing a gas impulse that destroys all spaces in the facility. Consequently, combat facilities are often subdivided by hardened partitions designed to limit the spread of damage to the room where the weapon perforated the structure. However, this strategy is often very expensive because the gas impulse generated by the explosion is large when the high-temperature gases are confined to a single room. Consequently, survivable structures against today's threats are very expensive, if not impractical! Any scheme that would reduce the magnitude of the gas impulse from the MCE would significantly reduce the structural cost of survivable combat facilities. Alternatively, any scheme that would reduce the magnitude of the gas impulse could be deployed today in existing combat facilities, thereby increasing the survivability of these facilities against enemy weapons!

2.5 Terrorist Bombings

Given a choice, terrorists will typically detonate bombs in a confined space, such as a lobby, to achieve maximum damage to a building. The damage enhancement results from the gas impulse associated with a confined explosion. Any scheme that would reduce the magnitude of the gas impulse would significantly reduce the structural cost of hardening confined spaces to protect sensitive facilities from terrorist bombings. Alternatively, any scheme that would reduce the magnitude of the gas impulse could be deployed today in confined spaces of sensitive facilities, thereby increasing the physical security of these facilities against terrorist bombings!

3.0 SOLUTION

3.1 Water Concept

The water concept requires water to be deployed in the near proximity, but not necessarily in contact, with the explosive material. The water must be in the near proximity of the explosive at all times when an inadvertent explosion is a credible event.

One possible concept for deploying the water is a water blanket, as illustrated in Figure 1. For the case of palletized ordnance, the water blanket would be draped over the top of each pallet of ordnance. The blanket(s) dedicated to a pallet of ordnance would contain a minimum amount of water, the amount depending on the type and NEW of high explosive stored on the pallet. In theory, TNT explosive would require about 1.8 lb of water for each pound of TNT while H-6 explosive would require about 3.8 lb of water for each pound of H-6. The blanket would be some commercial off-the-shelf design. The blanket material would be puncture resistant, yet not retard aerosolization of the water by the shock wave from an explosion. The blanket width would be fixed at about 38 inches, slightly less than the minimum width of any pallet of ordnance. The length and number of blankets dedicated to each pallet will vary, depending on the NEW and type of explosive stored on the pallet.

3.2 Phenomenon

Detonation of a high explosive produces high pressure shock waves which travel outward in all directions from the explosion at extremely high velocity. These high speed shock waves strike and aerosolize the water located in the near proximity of the explosion. The aerosolized water prevents combustion of detonation products by preventing access to oxygen and by cooling gases below the temperature required to sustain combustion. For this to occur, the aerosolized water must absorb the detonation energy of the explosive. Typical heats of detonation for high explosives range from 980 calories/gram for TNT explosive to 2030 calories/gram for H-6 explosive. Vaporization of water absorbs 539

calories/gram plus one calorie/gram/degree to heat the water to 100 degrees Celsius. Thus, the aerosolized water can absorb all of the detonation energy of the explosive if the weight ratio of water to explosive is 980/539 = 1.8 for TNT explosive and 2030/539 = 3.8 for H-6 explosive. These ratios assume the aerosolized water is 100% efficient in eliminating the heat detonation, thereby eliminating the heat of combustion and associated burning of explosive by-products in the air. In practice, the weight ratio of water to explosive should probably be slightly greater than the above values to account for less than 100% efficiency in eliminating the heat of detonation. In any case, the net effect of the water absorbing the detonation energy of the explosive is a major reduction in the peak gas pressure and total gas impulse from the confined explosion.

Ideally, the shock waves need to aerosolize the water very quickly (in a matter of milliseconds) into a fine mist of water droplets suspended in the atmosphere of the containment structure. Hence, the need for the sheet, layer, pillow or blanket of water to be located in the near proximity of, but not necessarily in contact with, the explosive producing the explosion. The water mist presents a <u>huge surface area</u> of water, an ideal condition for efficiently converting the water from a liquid state to a vapor state. The later-time buildup of high-temperature gases from the by-products of the explosion, expanding in a fully or partially confined space with restricted venting, cause huge amounts of energy released by the explosion to be quickly dissipated by changing the water mist from a liquid state to a vapor state. The consequence of this phenomenon is a peak gas pressure and total gas impulse much less (as much as 90% less based on test data) than the peak gas pressure and total gas impulse would have been in the absence of water.

The utility of the water concept is expected to diminish with an increasing ratio of net explosive weight to structure volume (W/V). Although there are no test data to prove this to be the case, certain negative factors are obvious at high values of W/V. For example, at some very high W/V, there is insufficient space to accommodate the volume of explosive (and the attached inert components) and water. Because of the volume of inert components, the critical W/V for bombs (high explosive density) would be higher than for containerized missiles (low explosive density). At some lower W/V, the available space can accommodate the volume of water and explosive items but there is insufficient air space inside the structure to allow the shock waves from the explosion to aerosolize the water. In this case, the total surface area of water-in-air is too low relative to its total weight, thereby preventing the gas temperatures from converting much water from the liquid state to the vapor state, and, hence, no significant absorption of the detonation energy by the water. A third constraint is the capacity of the structure to confine, at least partially, the explosion at the high shock plus gas pressures associated with a high W/V. Unless the structure can confine the high temperature gases for some minimum time, then the water cannot absorb much detonation energy from the explosive. Thus, there is some upper bound value of W/V that defines the limit for

application of the water concept. This critical value of W/V will vary of course, depending on several parameters, such as type of explosive, type of ordnance, logistics constraints, and the architectural and structural design of the containment structure.

The utility of the water concept is also limited by the capability of logistics systems to cope with the weight and volume of water needed to absorb the detonation energy of the explosive. However, it is anticipated that the water concept is a very practical, useful, cost effective concept for a very broad range of scenarios faced every day in the "explosives world," as illustrated by the broad range of applications described in Section 4.0 of this paper.

3.3 Demonstration Tests

Results from high explosive tests conducted by NSWC demonstrate that water can reduce the peak gas pressure and total gas impulse generated by fully and partially confined explosions. The NSWC tests were 1/12th scale model tests of storage cells in HP Magazines (Ref 5). The cells were 3-wall cubicles with water-filled walls, as shown in Figure 2a. The tests involved detonating a cylinder-shaped TNT charge (right cylinder with L/D = 1.0) at the geometric center of a 3-wall cell with water-filled walls. The water-wall cell rested on a table located inside a hardened, unvented, steel chamber that fully contained effects from the test explosion. In all tests, the weight of explosive, W, was 4.67 lb TNT, the test chamber volume, V, was 1,150 ft^3, and the vent area of the chamber, A_v, was 0 ft^2.

Typical plots of the gas pressure versus time measured inside the test chamber are shown in Figure 2b. The scope of these tests and the peak gas pressure measured inside the test chamber are summarized in the table below. Note that providing 2.89 pounds of water for each pound of TNT explosive (W_W/W = 2.89) reduced the peak gas pressure from 54.1 psi (average of tests 1 and 10) to 5.85 psi (average of tests 7 and 8) for a total reduction of nearly 90%!

Test No.	Test Configuration	TNT Weight W (lb)	Water Weight W_W (lb)	W_W/W	W/V (lb/ft^3)[a]	Peak Gas Pressure P_g (psi)[b]
1	Hung bare charge	4.67	0	0	0.00406	55.4
2	Bare charge on table	4.67	0	0	0.00406	51.3
3	Charge immersed in cube of water	4.67	9.0	1.93	0.00406	5.1
4	Charge immersed in cube of water	4.67	13.5	2.89	0.00406	4.4
5	3-Wall cubicle with 2" thick water walls	4.67	9.0	1.93	0.00406	8.3
6	3-Wall cubicle with 2" thick water walls	4.67	9.0	1.93	0.00406	7.5
7	3-Wall cubicle with 3" thick water walls	4.67	13.5	2.89	0.00406	5.9
8	3-Wall cubicle with 3" thick water walls	4.67	13.5	2.89	0.00406	5.8
9	Charge immersed in cube of ethylene glycol (50/50)	4.67	9.0	1.93	0.00406	6.0
10	Hung bare charge	4.67	0	0	0.00406	52.7

[a]Test chamber volume, $V = 1,150\ ft^3$; scaled vent area of test chamber, $A_V/V^{2/3}=0.0$.

[b]Average value from 11 pressure transducers located inside test chamber.

4.0 APPLICATION

4.1 Explosives Safety

Ordnance facilities house ordnance operations supporting the Naval Ammunition Logistics System (NALS). The designs for these ordnance facilities are heavily influenced by Navy explosives safety regulations intended to limit the risk of injuries and damage from an accidental explosion inside the facility. The ordnance facility is either a hardened design, resulting in a high construction cost to either fully or partially contain effects from an accidental explosion inside the structure, or an unhardened design, resulting in a high encumbered land cost to accommodate Explosives Safety Quantity Distance (ESQD) arcs. The following sections illustrate the potential applications and benefits of deploying water in ordnance facilities to significantly reduce the cost of facilities and land supporting the NALS.

4.1.1 X-ray Facilities. X-ray facilities are used to X-ray ordnance items and explosive components, such as warheads, projectiles, fuzes, and rocket motors, to evaluate their state of readiness. Radiography Building 35, Pittsburg, California, is a typical X-ray facility.

The USN AMHAZ Review Board recently reduced the NEW limit for Building 35 from 5,000 lb NEW to 50 lb NEW because of their concern about hazardous pressures, fragments, and debris at the government property line from the MCE in Building 35. The reduced NEW limit severely degrades the efficiency of X-ray operations. Consequently, Naval Weapons Station, Concord, California, contracted NCEL to evaluate the hazards and develop a risk mitigation strategy that would increase the safe NEW limit for Building 35 to at least 1,680 lb NEW.

Radiography Building 35 is a large, rectangular-shaped structure with very massive reinforced concrete walls and equipment door; a sloped, frangible, corrugated metal roof; and a small attached structure of conventional construction. The main structure has one large room, called the X-ray Exposure Room, where explosives are x-rayed. The floor plan, elevation view, and roof details are shown in Figure 3.

NCEL analyzed the hazards from Building 35 and concluded that the safe explosive limit is less than 10 lb NEW because damage to the frangible roof produces hazardous blast pressures and hazardous roof debris at the property line for an MCE $\geq$ 10 lb NEW (Ref 1). NCEL developed a risk mitigation strategy that increases the safe NEW limit from less than 10 lb NEW to at least 2,240 lb NEW. The strategy requires the following renovations to Building 35:

a. Require a water blanket to be part of each pallet of ordnance while the pallet is anywhere inside Building 35. The design and deployment concepts for the water blanket are shown in Figure 1.

b. Replace the existing corrugated metal roof with a precast, R/concrete roof, consisting of precast, R/concrete T-beams positioned side-by-side; a cast-in-place R/concrete topping slab; and a chimney

vent, as shown in Figures 4a and 4b. The average thickness of the R/concrete roof, T_c, is 18 inches. The chimney vent, located an equal distance from the property lines, restricts the venting of shock waves from the MCE in Building 35. This restriction limits the peak incident pressure at the property line to 1.2 psi maximum, the limit allowed by NAVSEA OP-5 safety regulations for the safety of people and property at government property lines. The cast-in-place, R/concrete topping slab provides a critical roof mass that controls the maximum strike range of roof debris, stops weapon fragments, slopes the roof for water runoff, and holds the T-beams together when the roof moves upward from effects of the MCE.

c. Add four ready-service magazines inside the building, each magazine separated by a nonpropagation wall, as shown in Figure 4c. The magazines are ventilated, skid-mounted, and relocatable. Designs are commercially available that meet all federal specs for safety and security of explosives storage. The magazines are sized to accommodate the water blanket draped over the top and down two sides of each pallet load. The nonpropagation walls prevent sympathetic detonation between any two magazines, thereby limiting the MCE to 560 lb NEW, the safe storage capacity of each magazine.

d. Conduct all ordnance receipt/shipment operations inside the building by parking the flatbed trailer (trailer containing the ordnance) inside the building with the entry door closed before any ordnance is transferred to or from the trailer. This arrangement mitigates the hazards associated with ordnance transfer operations, as shown in Figure 3a.

The water blanket is a major element of the risk mitigation strategy for Building 35. The shock wave from the MCE will aerosolize the water in the blanket, thereby allowing the water to absorb huge amounts of energy (that would normally create gas pressure) by changing the water mist from a liquid state to a vapor state. Consequently, the water blanket reduces the peak gas pressure and total gas impulse generated by the MCE. This reduction, in turn, reduces the maximum strike range of roof debris from about 124 ft (without water blanket) to about 12.6 ft (with water blanket), as shown in Figure 4d for $T_c = 18$ inch. Thus, the water blanket reduces the strike range of debris by 90%! To gain the same result without a water blanket would require a <u>12-ft deep soil layer</u> covering the entire 3,200 ft^2 area of the roof! This soil mass would weigh 2,112 tons! Thus, the water blanket eliminates the need to place 2,112 tons of soil on the roof which would be very expensive and surely impractical. Without the water blanket, NCEL found no practical strategy for increasing the safe explosive limit for Building 35 to the minimum limit needed for efficient ordnance operations.

4.1.2 Missile Maintenance Facilities. A Missile Maintenance Facility (MMF) is an intermediate-level maintenance activity for the assembly, repair, and testing of Navy missiles. A typical MMF is a very large, unhardened structure with R/concrete walls and a metal or R/concrete roof. The safe explosive limit for an MMF is usually less than 30,000 lb NEW, in which case the ESQD distance to nearby inhabited facilities is 1,250 ft. This ESQD arc encumbers at least 112 acres of land!

Missiles are delivered to the MMF in their container. Once inside the MMF, the missile is removed from its container and placed on a Missile Assembly and Maintenance (MAM) stand. The missile remains on the MAM stand during the entire maintenance cycle.

A water-filled cradle mattress could be a permanent part of the MAM stand, as illustrated in Figure 5a. By so doing, the proper amount of water would be deployed in the ideal locations of the MMF, i.e., in the near proximity of each explosive component in the MMF, regardless of when or where the missile was moved inside the MMF. Given an inadvertent explosion as illustrated in Figure 5b, the distribution of water throughout the MMF would be the ideal distribution at all times!

The MAM stand could easily accommodate the water mattress, without the mattress interfering with maintenance operations on the missile. If necessary, the water mattress could be located below the main beam assembly (Figure 5a) of the MAM stand.

The characteristics of the water mattress depend on the characteristics of the missile. The net explosive weight is less than about 300 lb NEW for most surface-launched missiles and less than about 100 lb NEW for most air-launched missiles. Based on a weight ratio of water-to-explosive equal to 2.0, the approximate characteristics of the water mattress would be as follows:

Missile Type	Maximum Explosive W (lb NEW)	Weight Ratio W_w/W	Water Quantity W_w (lb)	Water Quantity V_w (ft^3)	Mattress Size L x W x H
Surface Launched	300	2.0	600	9.6	10'x 2'x 0'-6"
Air Launched	100	2.0	200	3.2	6'x1'-6"x0'-4"

The mattress material would be puncture resistant, yet not retard aerosolization of the water by the shock waves from inadvertent detonation of the missile on the MAM stand.

The debris prediction model shown in Figure 6a was used to estimate the benefits of deploying water mattresses in a Missile Maintenance Facility and other similar types of unhardened, aboveground, ordnance facilities. The model is crude in terms of simulating the actual breakup pattern of the building envelope. However, the model correctly accounts for all critical parameters, including the following:

- The mass of the building envelope.
- The shock pressure loading applied to each individual building surface, as a function of time, based on the computer program SHOCK.
- The vent area created for gases to escape around the perimeter of each building surface, as a function of time, when these building surfaces are displaced outward by the internal gas and shock pressure loadings, based on computer program FRANG 2.0 which simultaneously tracks the displacement-time history of five building surfaces.
- The internal gas pressure, as a function of time, as the building vent area increases with time and allows gas pressures to vent from the building, based on computer program FRANG 2.0.
- The critical launch angle of debris from each building surface, based on the rotation capacity of the building envelope at its supports.
- The flight trajectory and strike range of building debris, based on computer program TRAJ.
- The reduction (assumed to be 89%) in the <u>initial</u> peak gas pressure due to the water, and the internal gas pressures at all subsequent times based on FRANG 2.0, using a pseudo explosive weight that would produce the <u>initial</u> peak gas pressure inside the building.

It was assumed that a typical building is L = 100' long, w = 50' wide, and H = 15' high. The MCE is assumed to be located at the center of the building, 4'-0" above the floor. The building envelope has no initial vent area, i.e., the building has no windows and no open doors. The mass of the building envelope, γ, is 25 psf minimum and 200 psf maximum. Breakup of the building envelope requires no work to be done, i.e., the strain energy absorbing capacity of the building envelope is zero. The critical mass of launched debris is 1.0 lb.

The benefits of the water mattress are described by the curves presented in Figures 6b, 6c, and 6d. The predicted reduction in the total gas plus shock impulse due to water, R_i (%), is presented in Figure 6b as a function of the net explosive weight, W, of the MCE and the unit mass, γ, of the building envelope. The predicted reduction in the debris distance due to water, R_d (%), is presented in Figure 6c as a function of W and γ. The predicted reduction due to water in the land area (including the area of the building footprint) encumbered by wall debris, R_A (%), accounting for differences in the debris distance from sidewalls and endwalls, is presented in Figure 6d, as a function of W and γ. Note in these figures that R_i, R_d, and R_A decrease with increasing W and decreasing γ, as one would expect. Most important, these figures forecast that major reductions in the land area encumbered by building debris can be achieved by deploying water mattresses on MAM stands in Missile Maintenance Facilities! The reduction in encumbered land area,

R_A, ranges from 75 to 90% for W < 1000 lb NEW, from 20 to 75% for W = 1000 lb NEW, and from 15 to 50% for W = 30,000 lb NEW! These reductions represent huge savings in valuable waterfront real estate needed to protect people and property from accidental explosions in ordnance buildings! NCEL could not identify an alternative strategy that even approaches the cost- benefit of the water concept.

4.1.3 Missile Test Cells. The standard design for a NAVFAC Type I Missile Test Cell (MTC) is shown in Figure 7a. The MTC is used to test the reliability of all-up-round (AUR) missiles before delivery to the Fleet.

A mishap during the test could lead to inadvertent detonation of the missile. Consequently, the AUR test is conducted remotely from a control room located in the adjoining Missile Maintenance Facility.

The MTC is a massive reinforce concrete, box-shaped structure, as shown in Figure 7a. The interior of the box is 40'-0" long, 25'wide, and 15' high. The floor, roof and 3 walls are blast hardened to prevent the escape of blast pressures, weapon fragments, and debris. The fourth wall is a frangible wall, as shown in Figure 7a. This frangible wall is designed to fail and vent explosion effects in a safe direction away from the adjoining Missile Maintenance Facility.

The test missile is restrained on a test restraint fixture about 3'-6" above the MTC floor, as shown in Figure 7a. The MTC houses various test support equipment and an overhead bridge crane which travels the length of the MTC. The bridge crane is used to position the test missile on the test restraint fixture.

A water pillow could be deployed in the MTC, as illustrated in Figure 7b. Given a mishap during the AUR test, the shock waves from the MCE would aerosolize the water, thereby reducing the total gas impulse generated inside the MTC. The water pillow would be moved into position, directly over the test missile, with the bridge crane just before the MTC is evacuated to begin the AUR test. The water pillow would be suspended from the bridge crane, maybe 3 or 4 feet above the test missile, for the duration of the AUR test.

The chart in Figure 7c illustrates the potential benefit derived from the water pillow. The two curves in Figure 7c describe the total shock plus gas impulse, $i_g + i_s$, applied by the maximum credible explosion, W, to the ceiling of the MTC, with and without the water pillow. These curves were generated using computer programs SHOCK and FRANG, based on a frangible wall mass, γ = 30 psf; a design explosive weight equal to 1.2 W; and the MCE located at midlength of the box, 3'-6" above the floor.

The water pillow could significantly increase the safe explosive limit for an existing MTC. From Figure 7c, the water pillow reduces the total gas plus shock impulse by about 78% for W = 100 lb NEW, by about 37% for W = 300 lb NEW, and by about 27% for W = 1000 lb NEW!

The NAVFAC Type I MTC was designed for a safe explosive limit of W = 300 lb NEW which according to Figure 7c will apply $i_g + i_s$ = 16,000 psi-msec to the ceiling of the MTC. Therefore, if the total impulse

capacity of the ceiling is 16,000 psi-msec then it follows from Figure 7c that the water pillow could increase the safe explosive limit to about W = 780 lb NEW or 160%! Actually, the explosive limit is more likely to increase about 100% or to W = 600 lb NEW, because the duration of the gas impulse exceeds the time required for the ceiling slab to reach its maximum deflection. In any case, deployment of the water pillow concept could significantly increase the safe explosive limit of existing missile test cells!

The water concept would require the pillow to hold about 600 lb NEW x 2.0 = 1200 lb or 1200 / 62.4 = 19 ft^3 of water for W = 600 lb NEW. The weight ratio 2.0 accounts for propellant in missiles. Assuming an average missile is about 12' long, the pillow would be about 12'long, 2' wide, and 0'-9" thick. The bridge crane in existing MTCs could easily support this pillow load and there is ample space above the test restraint fixture to position the water pillow directly above the test missile.

4.1.4 Ready Service Magazines. Ready Service (RS) magazines are small, earth-covered, box-shaped, reinforced concrete structures designed to store small quantities of high explosives. Typical RS magazines have a storage capacity of about 100 lb NEW and their ESQD arcs encumber as much as 112 acres of land to protect people and property from an accidental explosion. Deployment of water blankets in RS magazines would significantly reduce the land area encumbered by ESQD arcs, especially if the water concept was combined with the use of non-propagating walls designed to reduce the MCE in RS magazines. Further, the water concept may allow RS magazines to be sited closer to the operating buildings they are intended to support.

4.1.5 Missile Storage Magazines. Missile Storage (MS) magazines are large, earth-covered, box-shaped, reinforce concrete structures used to store containerized, all-up-round missiles. A typical MS magazine is the NAVFAC Type C magazine. The magazine interior is 94'-8" wide, 50' deep, and 15' high which contains about 71,000 ft^3 of air space. To facilitate the storage and retrieval of containers, the magazine is used to store no more than about 120 large missile containers or about 14,000 ft^3 of cargo. This number of containers represents no more than about 60,000 lb NEW. Thus, only about 20 percent of the magazine space is used to store missiles. This storage plan provides an explosive density for the magazine equal to 60,000 lb NEW ÷ 71,000 ft^3 of space = 0.85 lb NEW/ft^3 which is relatively high compared to the range of existing test data ($4x10^{-3}$ lb NEW/ft^3 of space). Preliminary calculations indicate that water blankets deployed over missile containers may not reduce the ESQD arcs and associated encumbered land area by very much. However, test data need to be collected in this W/V range to determine if the benefits of deploying water blankets in MS magazines are significant enough to be used in this application.

4.2 SURVIVABILITY

Structural survivability of today's combat facilities is difficult to achieve, given the extreme accuracy and penetrating power of today's weapons. Even massive amounts of reinforced concrete, steel, soil cover, and rock rubble can fail to prevent today's weapons from perforating an interior space. Once inside the structure, detonation of the warhead constitutes a fully confined explosion, developing a gas impulse that destroys all spaces in the facility. Dispersion of resources is often the only practical strategy to achieve reasonable levels of survivability, but this strategy is very expensive. The following section illustrates a potential application and the benefits of deploying water in combat facilities to reduce the construction cost and increase the survivability of the structure.

4.2.1 Command and Control Centers. A Navy Command and Control Center is shown in Figure 8. The structure is a deeply buried, R/concrete structure subdivided into rooms by partitions designed to confine explosion effects to the room where the enemy weapon happens to perforate the structure.

Water blankets could be deployed in a Command and Control Center, as illustrated in Figure 8. The water blankets could be suspended from the ceiling or hung as drapes near the walls of each room. Given that an enemy weapon perforates the structure, the shock waves from the explosion would aerosolize the water, thereby reducing the peak gas pressure and the total gas impulse generated inside the room where the explosion occurs.

The water blankets would significantly reduce the structural cost of new Command and Control Centers, and significantly increase the survivability of existing Command and Control Centers! For most deep penetration weapons, the ratio of warhead explosive weight, W, to room volume, V, is probably no greater than the W/V ratio of existing test data ($W/V = 0.004\ lb/ft^3$). Consequently, the water blankets could be expected to reduce the peak gas pressure and total gas impulse by nearly 90%, based on test results presented in Section 3.3.

If the design threat was a 100 lb NEW warhead, then the water blanket must contain about 100 x 2.5 = 250 lb of water or 250/62.4 = 4 ft^3 of water. This quantity of water could be conveniently supplied by one blanket per room, measuring about 6' long x 4' wide x 0'-2" thick. The blanket could be either suspended 2 or 3 ft below the ceiling or hung as a drape at some minimum standoff distance from the nearest wall.

The water blanket concept offers significant increases in survivability and reductions in construction cost. In existing facilities, a 90% reduction in the peak gas pressure, P_g, translates into about a 90% reduction in the maximum dynamic deflection of the partitions, resulting in major reductions in damage to existing facilities. In new facilities, a 90% reduction in P_g reduces the required thickness of partitions by at least about 50%, resulting in major reductions in the construction cost of blast resistant partitions and doors. These potential benefits need to be quantified in more detail.

4.3 Physical Security

The water concept offers a cost effective strategy for quickly upgrading the physical security of sensitive facilities against terrorist bomb threats.

4.3.1 Terrorist Bombings. Physical security of sensitive facilities is difficult to achieve against the threat of terrorist bombings. Detonated in any fully or partially confined space, the confined explosion will develop a significant gas pressure impulse that can cause major damage to a facility. Water blankets or water drapes could be concealed in confined spaces of the facility, thereby reducing the gas impulse and associated level of damage to the facility.

4.4 Explosive Ordnance Disposal

The water concept could enhance the safety and capability of Explosive Ordnance Disposal (EOD) teams when transporting explosive devices to disposal sites.

4.4.1 Bomb Carts. A bomb cart is a mobile containment vessel used to transport explosive devices. The vessel is designed to fully contain explosion effects if the explosive device(s) were to detonate inside the vessel. A typical bomb cart is shown in Figure 9. Located inside the vessel is a basket formed from wire screen. The bomb is carried in the basket which holds the bomb a minimum standoff distance from the walls of the containment vessel.

Water-filled hotdogs could be hung at several points along the outer perimeter of the bomb basket, as shown in Figure 9. Given an accidental explosion, the shock waves from the explosion would aerosolize the water, thereby reducing the peak gas pressure generated inside the containment vessel. Depending on the bomb's explosive weight and the containment vessel volume, the aerosolized water could absorb the detonation energy of the explosive, thereby reducing the peak gas pressure by as much as 90 percent. Thus, the water hotdogs could significantly increase the explosive weight capacity of existing bomb carts and significantly reduce the fabrication cost of new bomb carts.

5.0 BENEFITS

Major benefits can be realized by deploying the water concept to mitigate the gas pressures from confined explosions. The major benefits include:

- Major reductions in the structural cost of containment structures designed to either fully or partially contain effects from an internal explosion.

- Major reductions in the land area encumbered by ESQD arcs designed to protect people and property from explosions in ordnance facilities.

- Major increases in the explosive limit of existing facilities that fully or partially confine an internal explosion.

- Major reductions in the extent of damage to existing facilities from an internal explosion.

6.0 RECOMMENDATIONS

- Begin research on water concepts in FY93. The magnitude of the potential benefits to the Department of Defense justify initiating the project immediately.

- A major research project should be initiated to develop the design criteria needed to safely deploy water that mitigates effects from confined explosions in new and existing facilities.

7.0 REFERENCES

1. Naval Civil Engineering Laboratory. Memorandum to files on the analysis of blast and debris hazards for safe explosives limit of ordnance operations in Radiography Building 35, Pittsburg, California, by P.C. Wager and W.A. Keenan, Port Hueneme, CA, Nov 1991.

2. Naval Civil Engineering Laboratory. Memorandum to files on the NCEL proposal for development of design criteria to mitigate blast, fragment, and debris hazards at property line from ordnance operations in Radiography Building 35, Pittsburg, California, by W.A. Keenan and P.C. Wager, Port Hueneme, CA, Jun 1992.

3. Naval Civil Engineering Laboratory. Technical Note N-1706: Basis of Design Document for Explosives and Contamination Safety of MCON Project P-312M, Reentry Body Complex, SWFLANT, Kings Bay, Georgia, by W.A. Keenan, et al., Port Hueneme, CA, Sep 1984.

4. Naval Civil Engineering Laboratory. Technical Note N-1752R: Basis of Design for NAVFAC Type I Missile Test Cell, by W.A. Keenan, R.N. Murtha, et al., Port Hueneme, CA, Apr 1990.

5. Wilson, David T. "Explosion Suppression by Water Surrounds," Paper presented at the Eighth IEP ABCA-7 Quadripartite Conference, 11-15 May 1992, Halifax, Nova Scotia, Canada. CONFIDENTIAL.

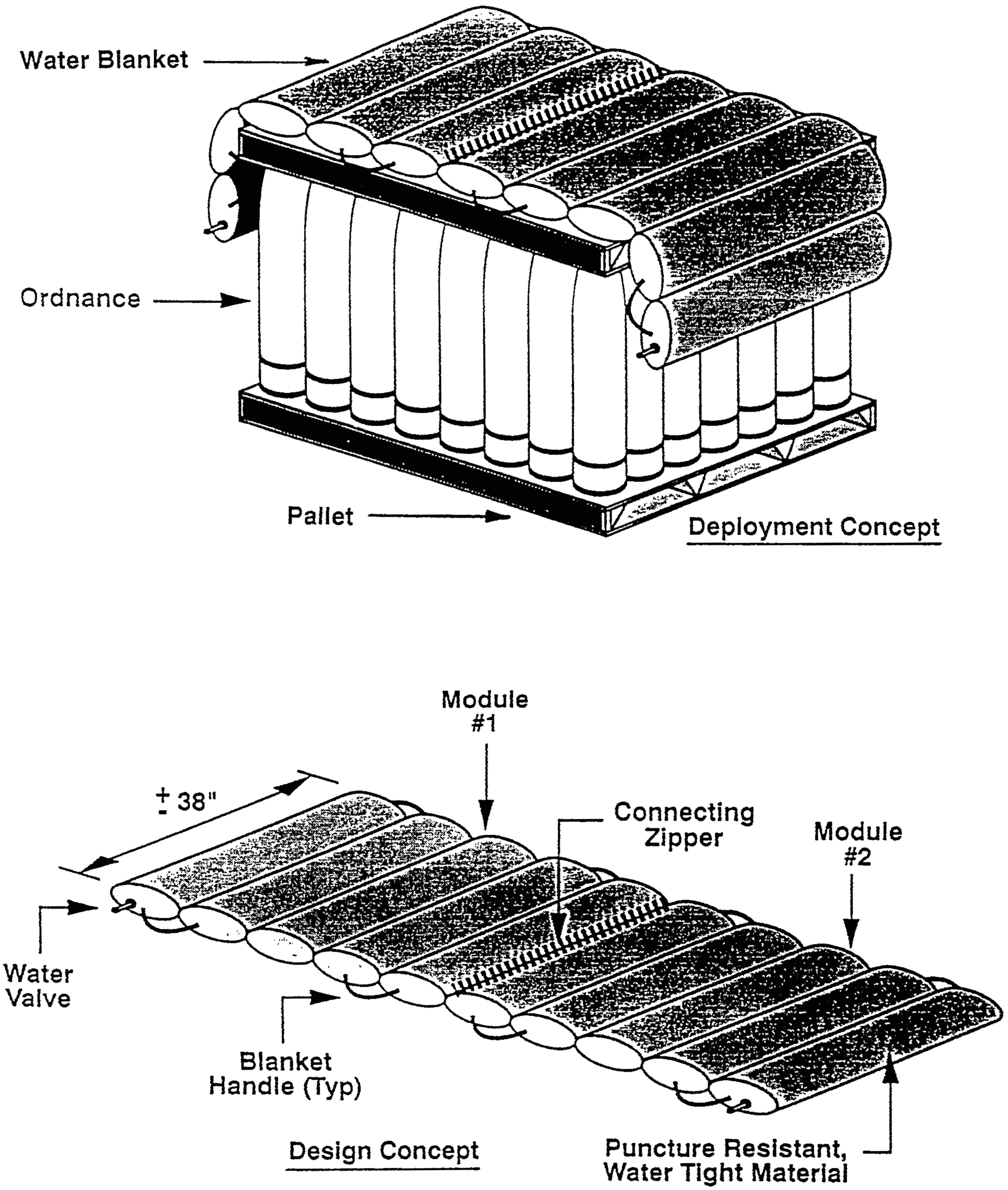


Figure 1. Conceptual design and deployment of water blanket.

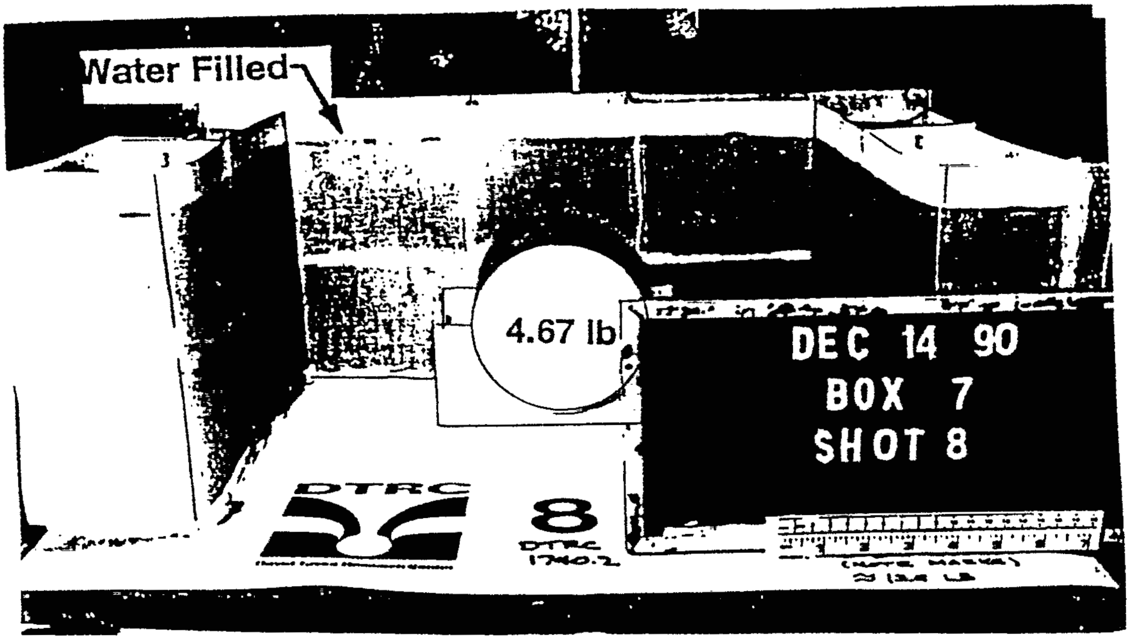
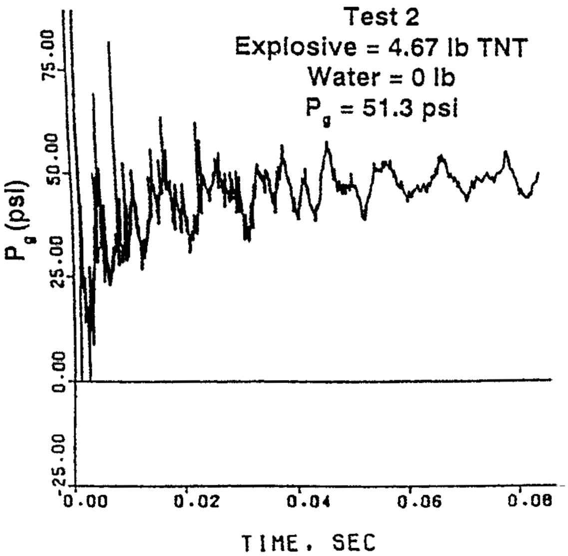


Figure 2a. Typical setup for NSWC tests showing water filled cell located on a table inside an unvented test chamber with test explosive located at geometric center of the 3-wall cell.



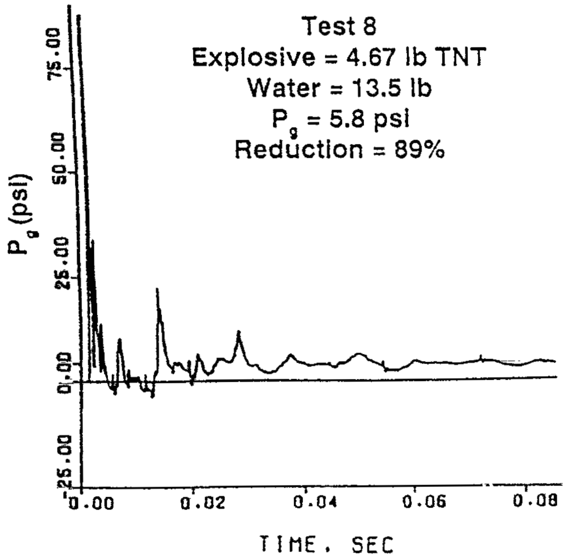


Figure 2b. Gas pressure versus time measured inside unvented test chamber from detonation of test explosive without water-filled walls (Test 2) and with water-filled walls (Test 8).

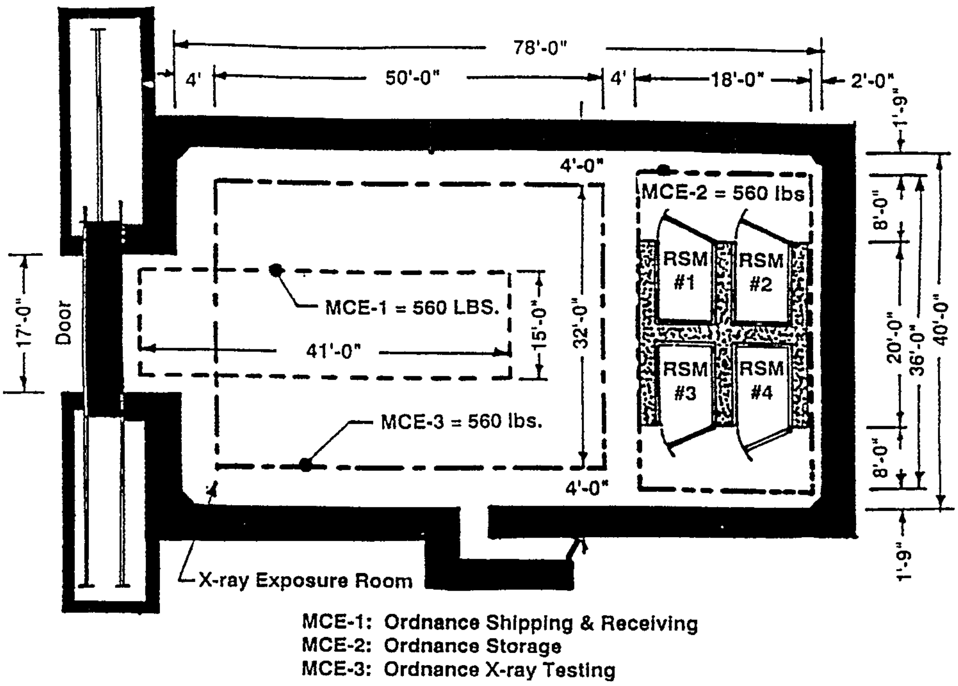


Figure 3a. Floor plan and MCE envelopes - Radiography Building 35, Pittsburgh, CA.

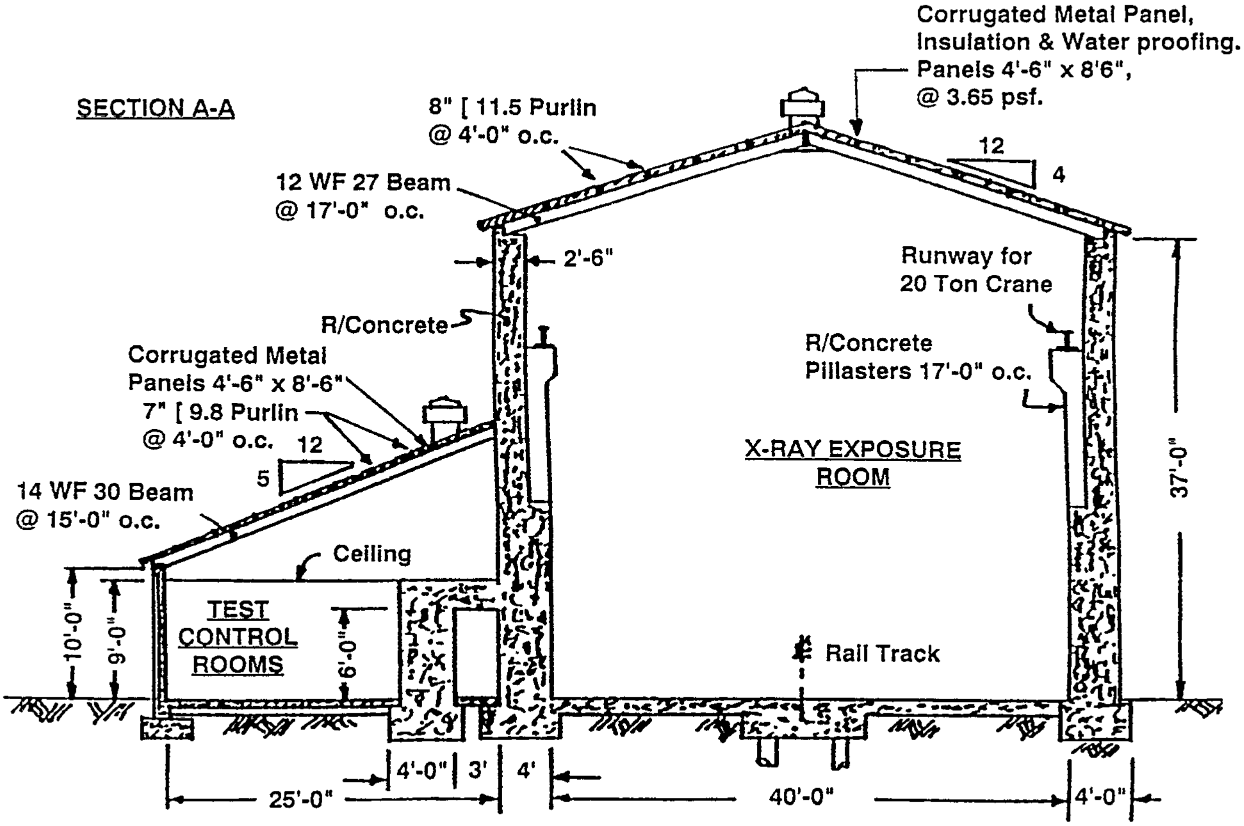


Figure 3b. Elevation view - Radiography Building 35, Pittsburgh, CA.

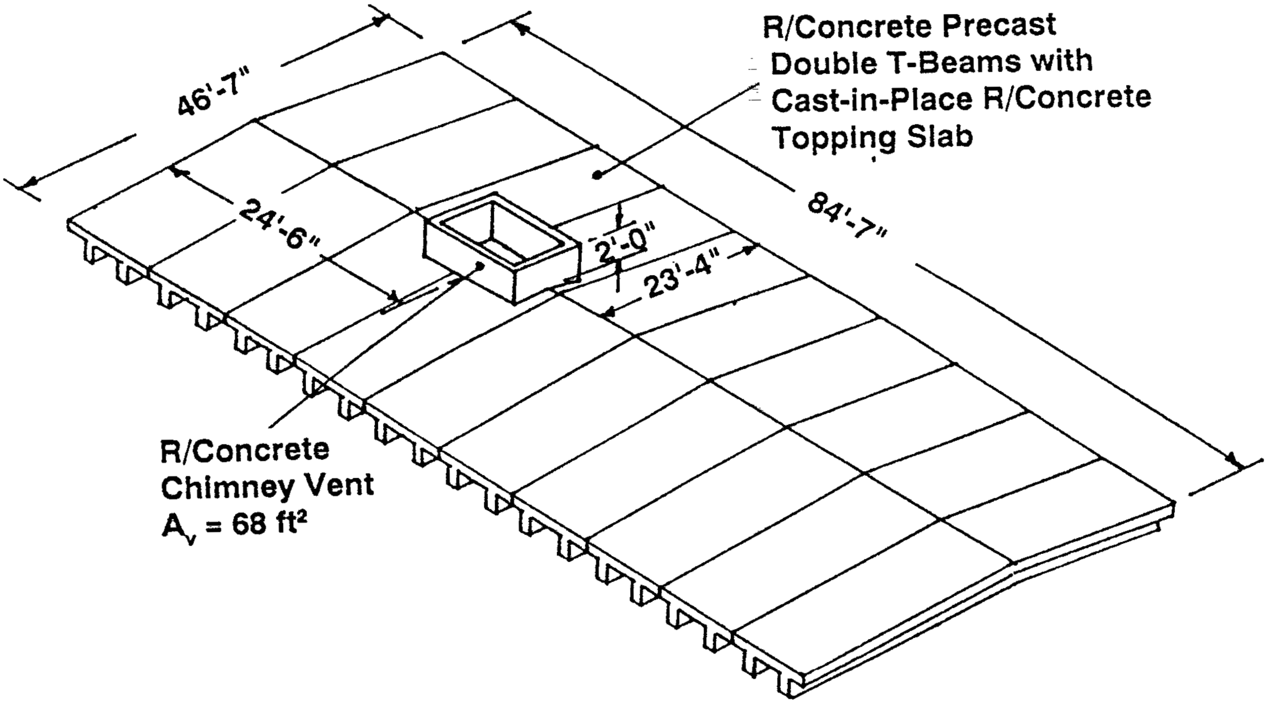


Figure 4a. Conceptual design of new roof and chimney for Building 35 - precast R/concrete T-beams with cast-in-place topping slab.

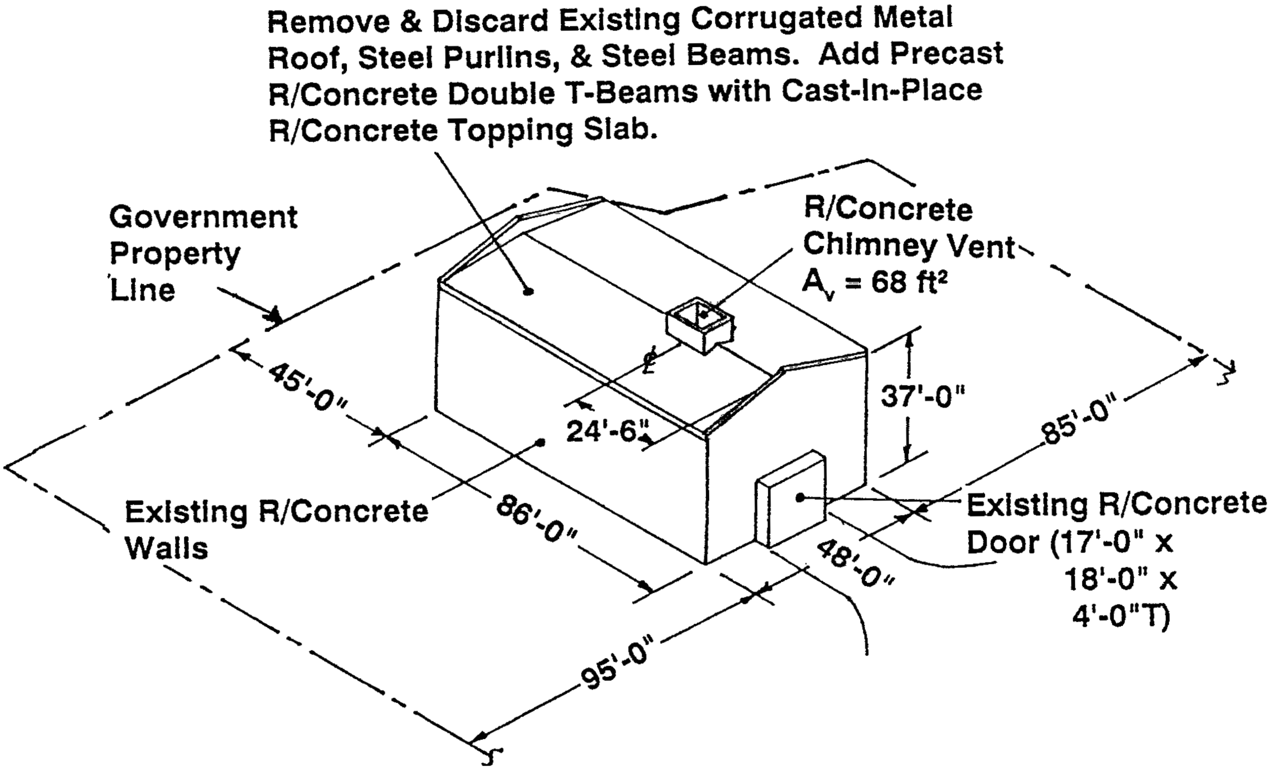


Figure 4b. Conceptual design of new roof and chimney vent to mitigate hazardous blast pressures, weapon fragments, and facility debris at government property line.

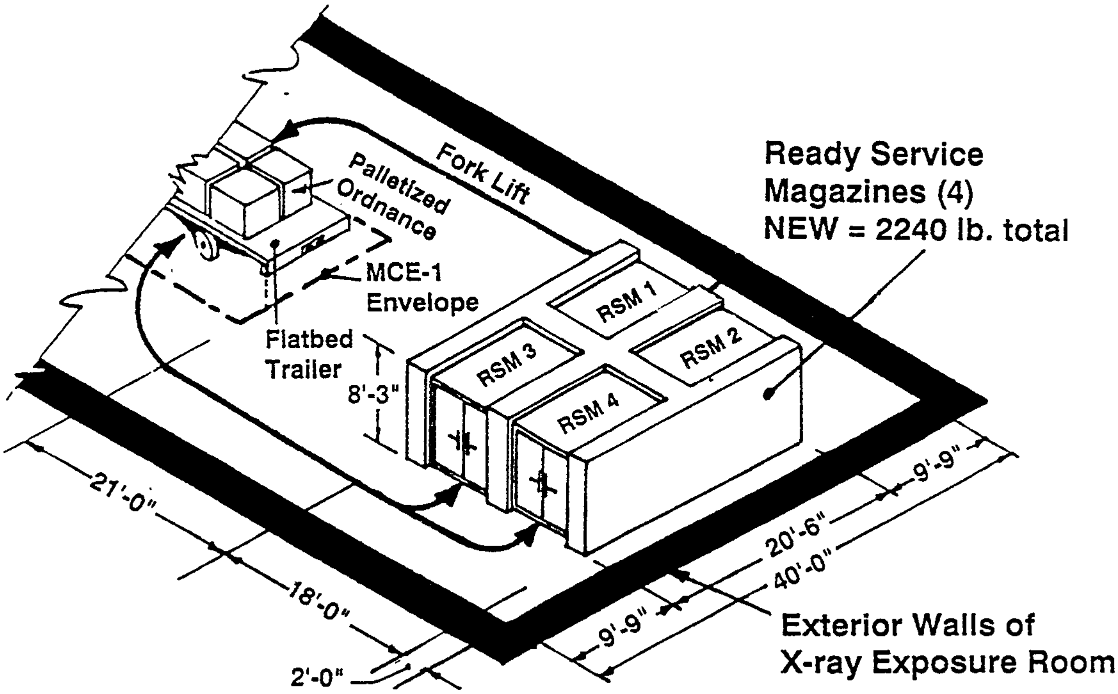


Figure 4c. Conceptual design and arrangement of four ready-service magazines to safely store 2,240 lb NEW and limit and MCE to 560 lb NEW.

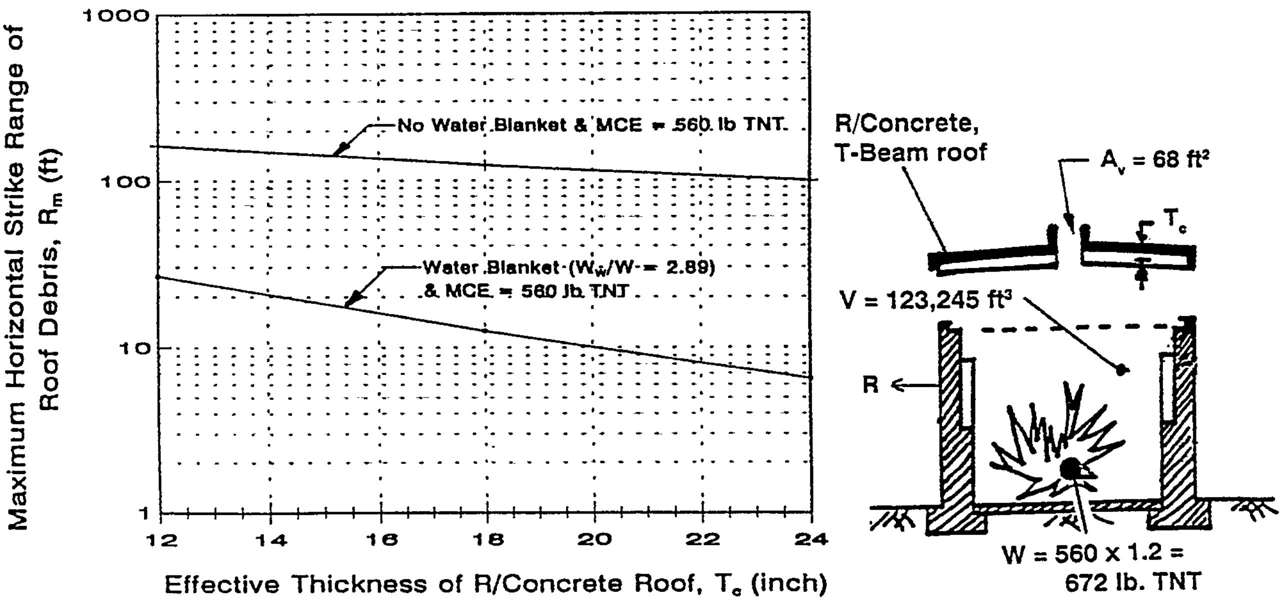


Figure 4d. Effect of water blanket on maximum strike range of R/concrete roof debris for MCE = 560 lb NEW.

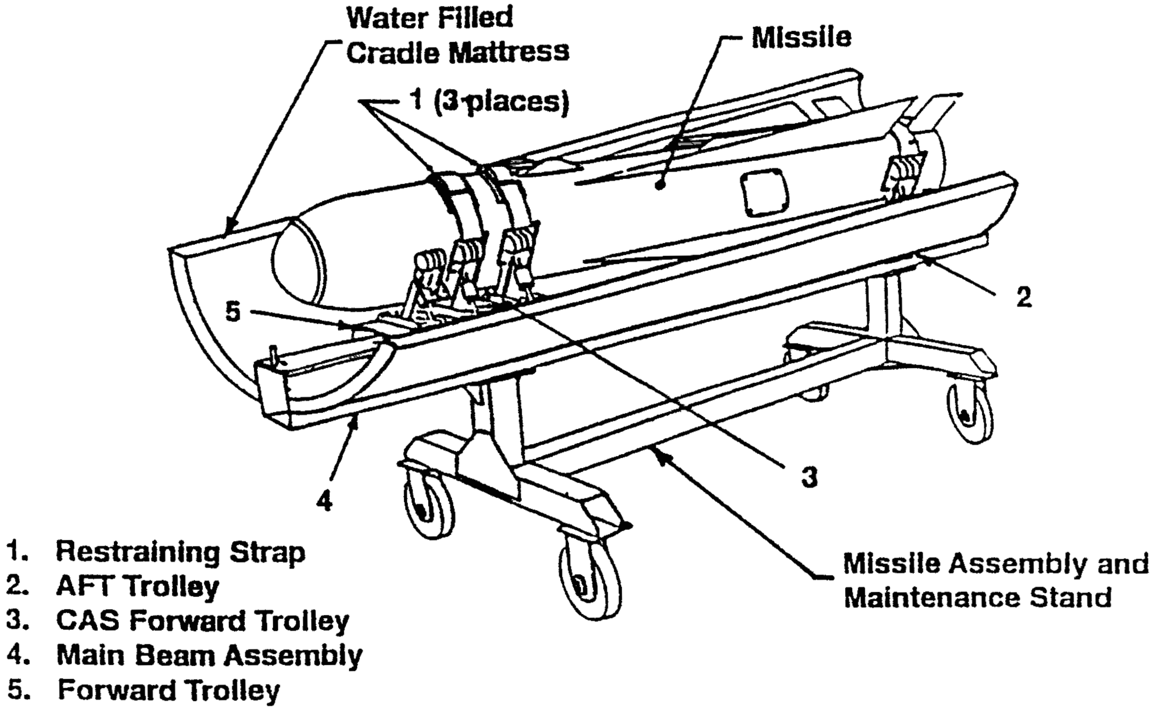


Figure 5a. Conceptual design of water mattress deployed on a Missile Assembly and Maintenance Stand.

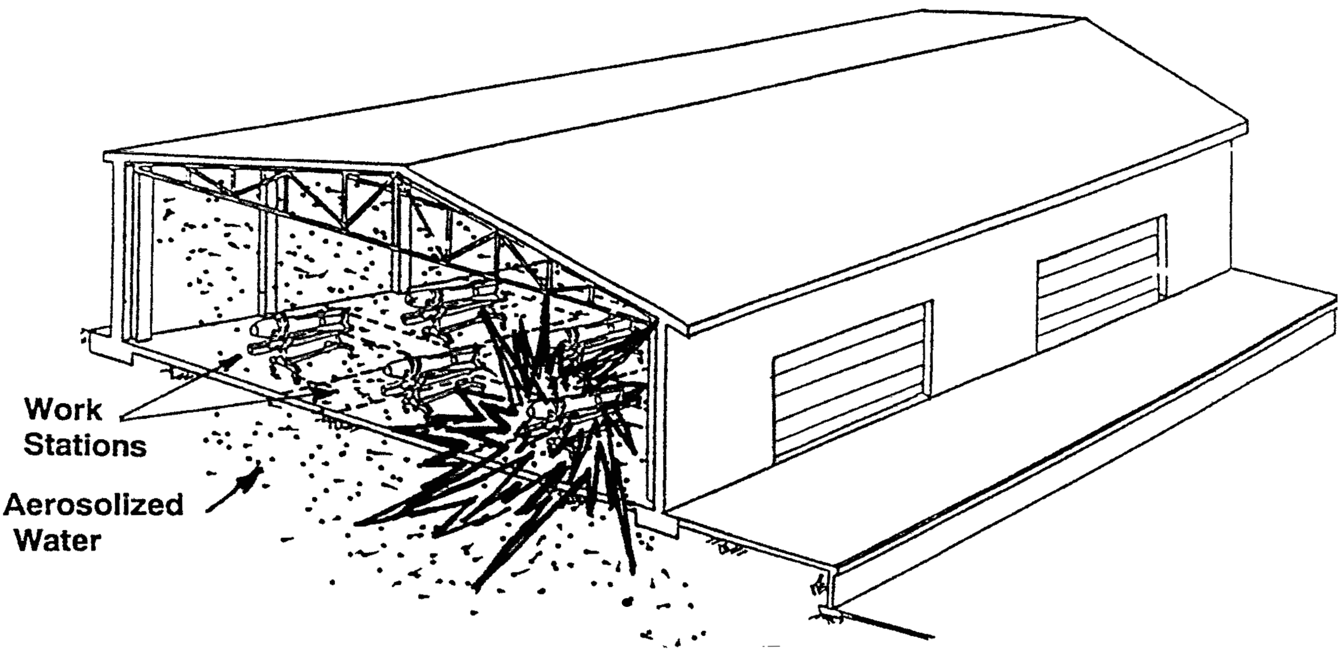


Figure 5b. Missile Maintenance Facility - missiles at their work stations with water deployed on Missile Assembly Stands when explosion occurs.

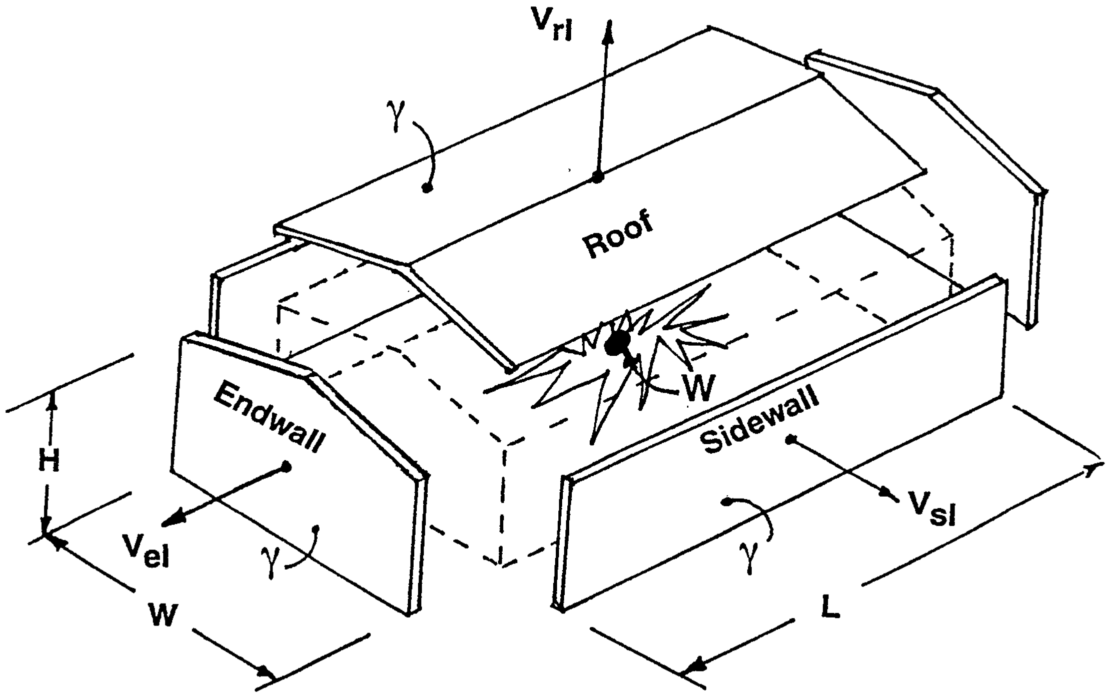


Figure 6a. Debris prediction model - assumed breakup pattern for a building.

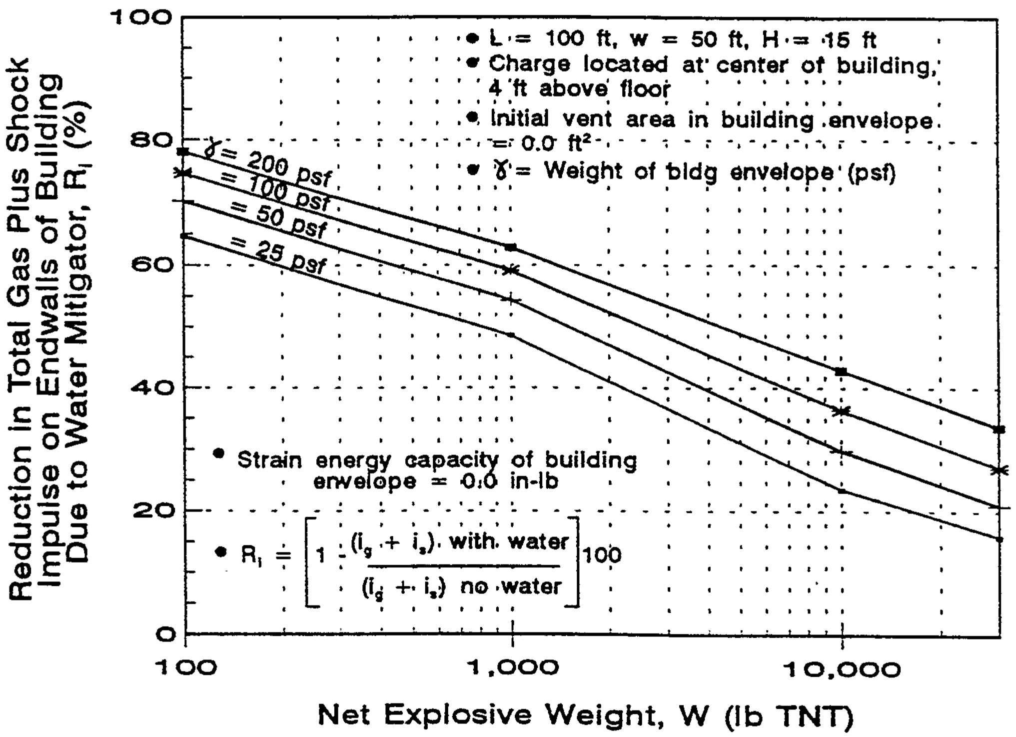


Figure 6b. Reduction in total gas plus shock impulse ($i_g + i_s$) acting on endwalls of building from water mitigator, as a function of net explosive weight (W) and weight of building envelope (γ).

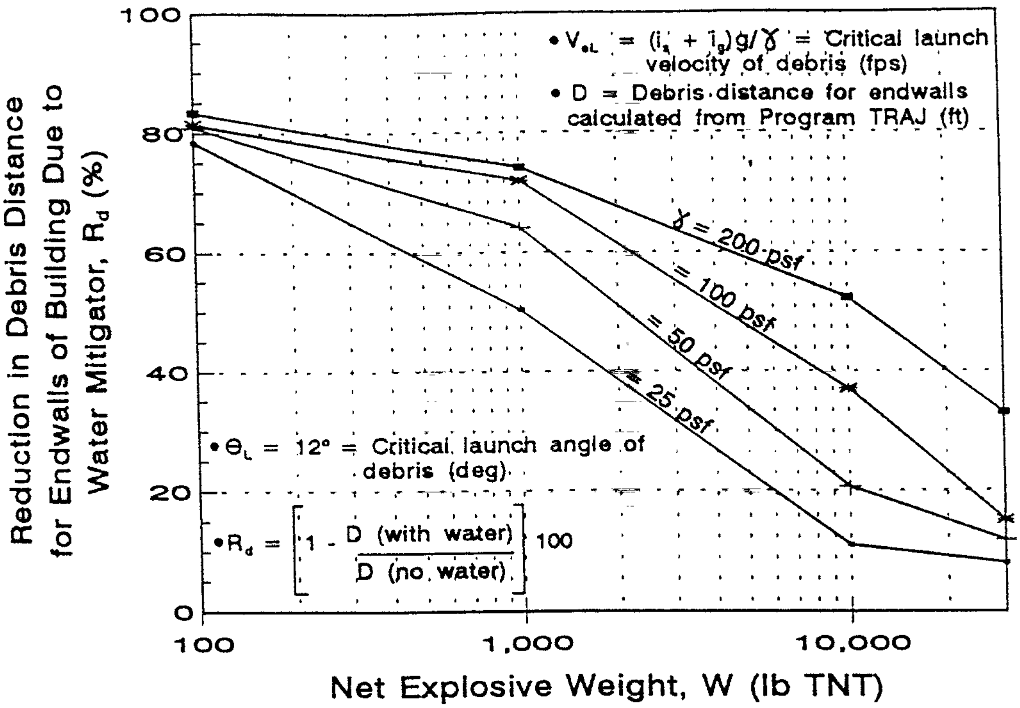


Figure 6c. Reduction in debris distance (R_d) from water mitigator as a function of net explosive weight (W) and weight of building envelope (γ).

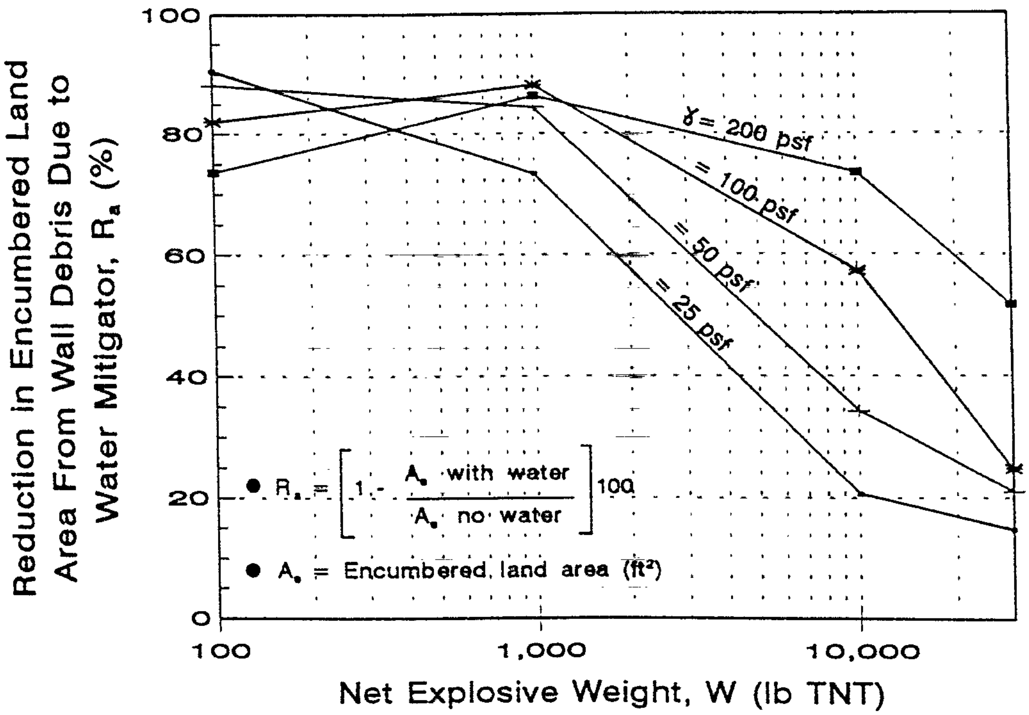


Figure 6d. Reduction in encumbered land area (R_a) from water as a function of net explosive weight (W) and weight of building envelope (γ).

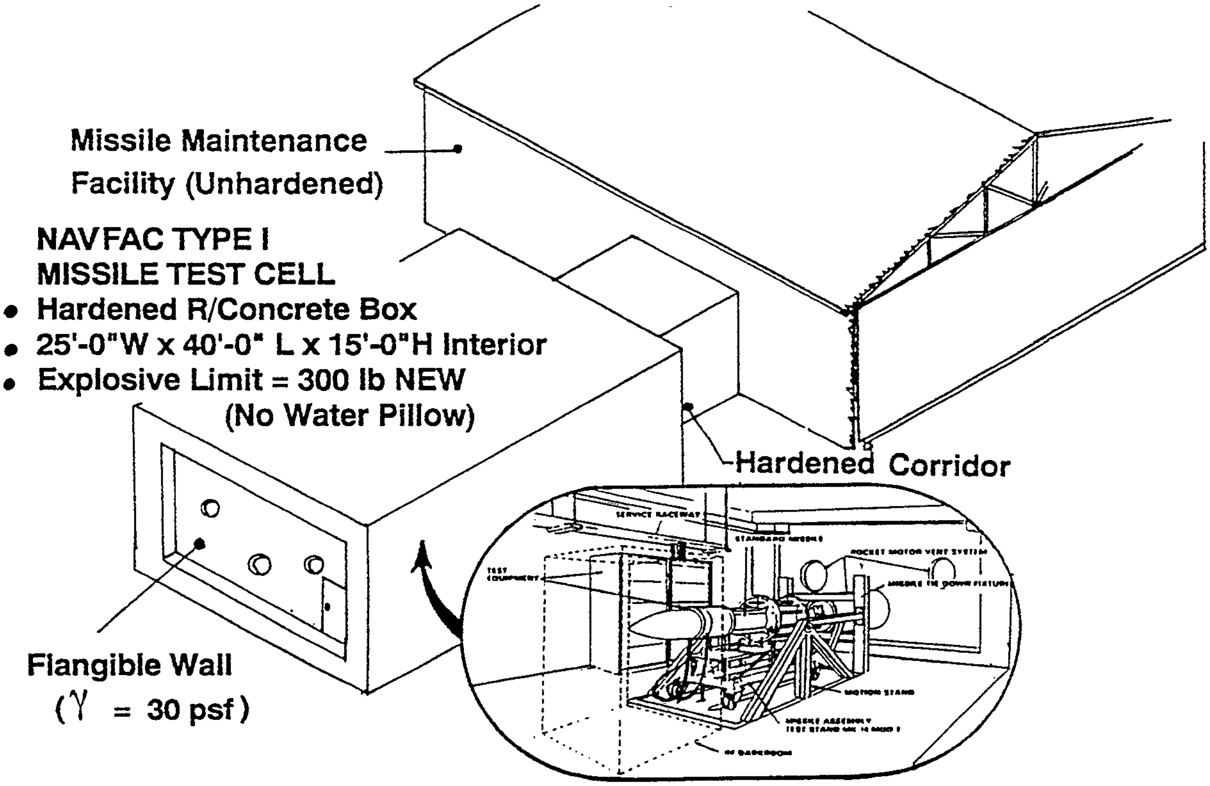


Figure 7a. NAVFAC Type I missile test cell adjacent to Missile Maintenance Facility for all-up-round testing of missiles.

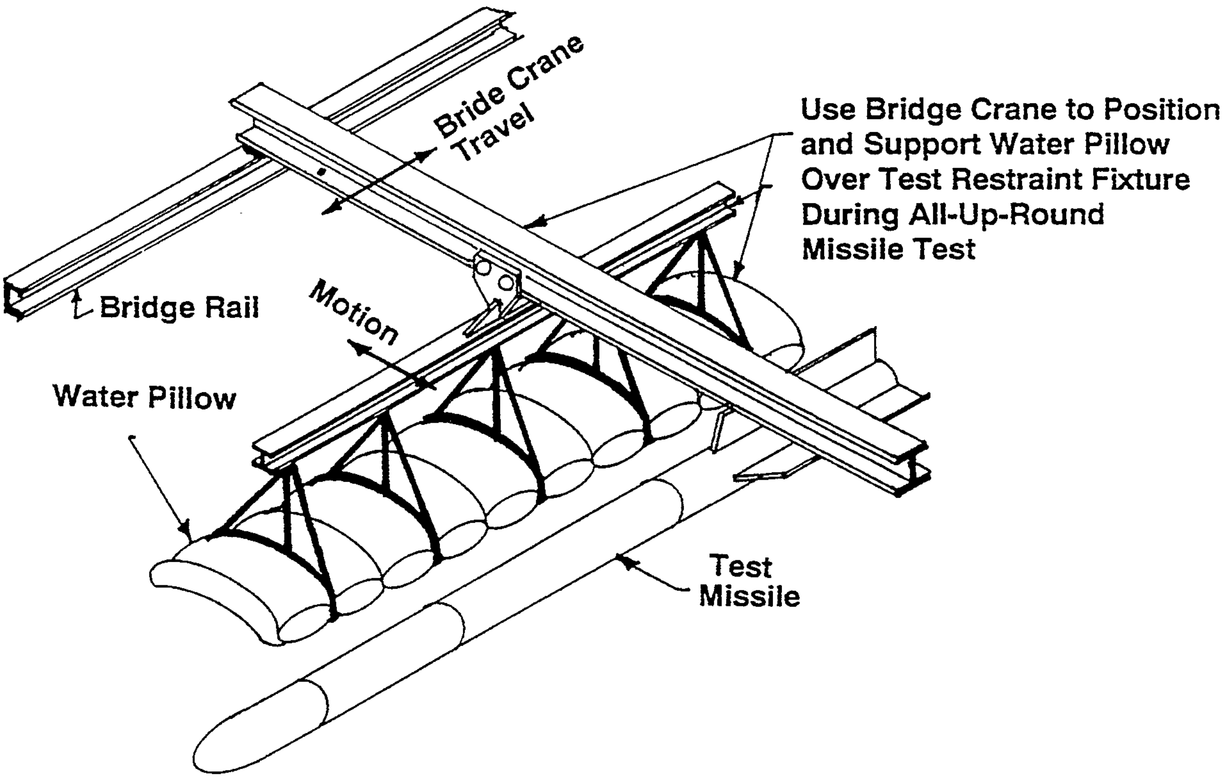


Figure 7b. Conceptual design of water pillow deployed above all-up-round missile in missile test cell.

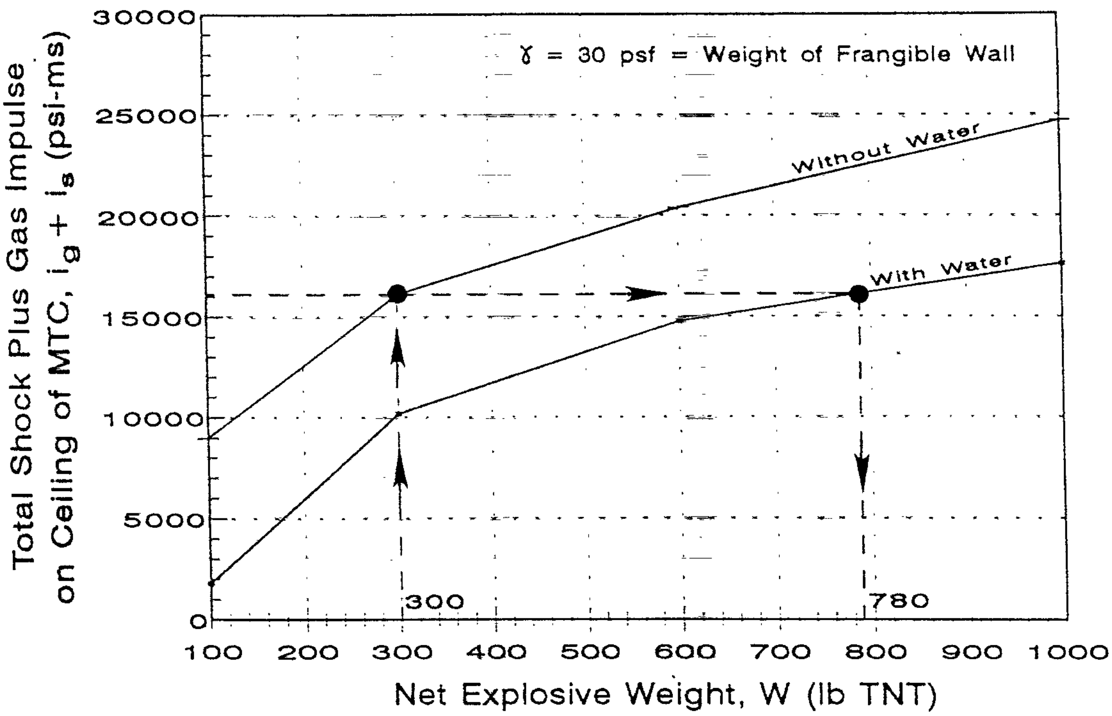


Figure 7c. Increase in explosive weight capacity of NAVFAC Type I missile test cell by deploying water pillow.

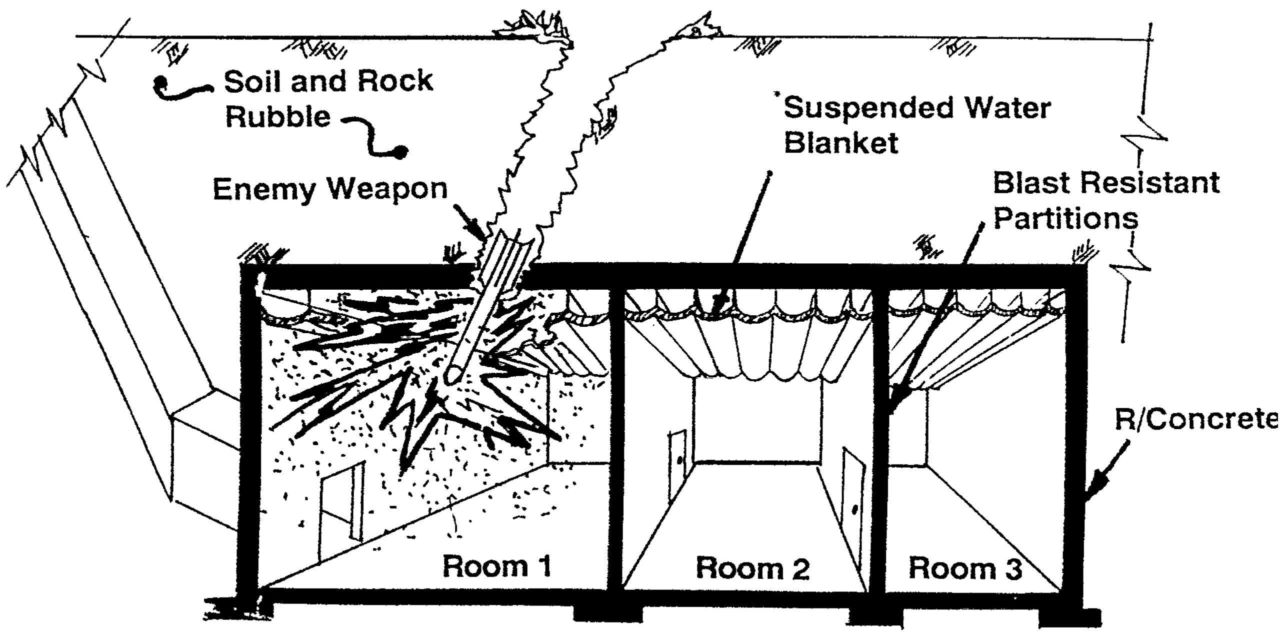


Figure 8. Navy Command & Control Center - water blanket suspended from ceiling to enhance survivability against penetrating weapons.

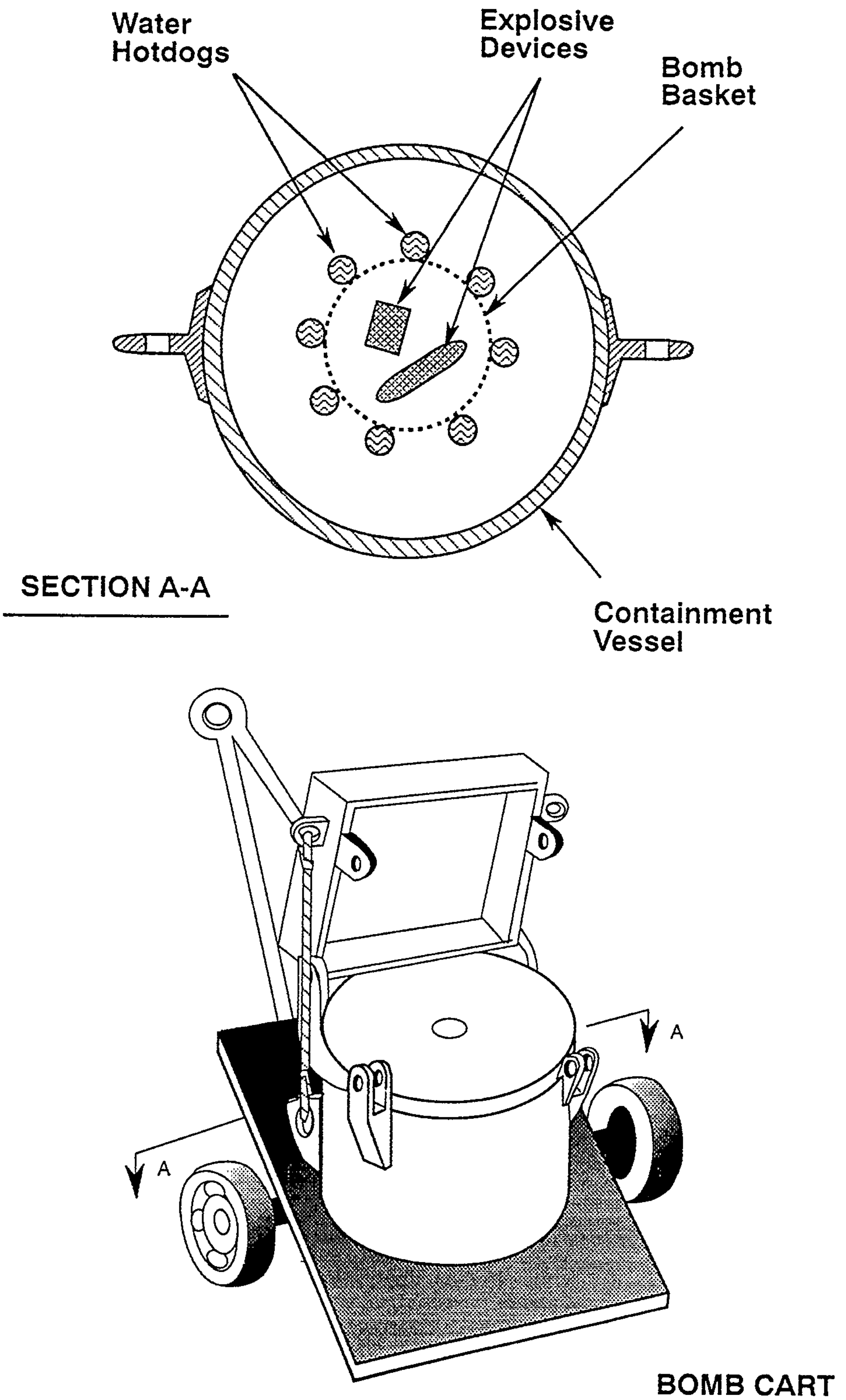


Figure 9. Conceptual design of a bomb cart with water hotdogs suspended from outer rim of bomb basket.